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MATHEMATICAL MODELING AND OPTIMAL CONTROL OF THE SEED SOWING PROCESS BY A DOTTED-NEST SOWING MACHINE

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Abstract: The research work presents a method for assessing the qualitative performance of a sowing machine using the dotted-nest seeding method. The analysis of the subject area is carried out, within which the object of optimization was described. The task of optimally determining the quality of sowing is set, for which a mathematical model has been developed. A criterion for evaluating the accuracy of sowing soybean seeds using the dotted-nest method was determined. For this purpose, the methods of planning a multifactorial experiment, statistical analysis, optimization, and decision theory were used. Two indicators are considered as optimization criteria to evaluate the seeding quality: the coefficient of variation of the time intervals between seed releases from the seeding disc and seed fragmentation, both of which are minimized. The optimization parameters chosen were two factors affecting seeding quality: the rotation frequency of the seeding disc and the position of the seed ejector. The optimization problem was addressed by constructing the Pareto front and using the exhaustive search method.

Introduction

Sowing takes a leading place in the technology of cultivation of agricultural crops. The efficiency of the technology depends to a greater extent on seeding. The main task of sowing is the optimal placement of seeds, ensuring maximum yield. At the same time, three basic requirements are imposed on sowing as a technological process: sowing a given number of seeds per unit field area; their uniform placement over the field area; sealing them to a certain (equal) depth [1].

Automation of sowing processes plays a crucial role in modern agriculture. It allows to increase the efficiency of resource use, provides a more accurate distribution of seeds, regulates the depth of seeding and the distance between plants, which leads to higher yields and reduces the need for manual labor. Additionally, automation reduces the risk of errors and enables to quickly respond to variable conditions, which is particularly important in agriculture where the influence of natural factors on work results is unpredictable. All this together contributes to increasing the efficiency of agricultural production and improves the economic sustainability of agricultural enterprises [2].

The seeding process on the seeders is monitored using control systems. The functions of the control system are to collect information about the operation of each sowing section, selection (filtering of the obtained values according to a set criterion), analysis of the process, display on the monitor (indicator) current information about quality, speed, etc., as well as messages about disruptions of the seeding process and the place of disruption [3]. In this case, seeding accuracy is calculated as the number of seeds per the path traveled by the seeder to the established seeding rate. It is controlled after the operation of the seeder by calculating the number of seeds per meter and the distance between the them, and it is estimated using the coefficient of variation.

With uniform sowing at the same intervals between seeds, the coefficient of variation tends towards zero. The value of the coefficient of variation less than or equal to 33% indicates the accuracy of seeding that meets agrotechnical requirements [4].

One of the most promising methods of seeding is a wide-row dotted-nest, in which seeds are distributed in groups of several pieces instead of traditional solid rows. This method provides better lighting, which contributes to a more complete development of the root system and aboveground parts of plants, which helps strengthen the lower beans on the plants and reduces losses during harvesting [5].

When using the dotted-nest sowing method, the distance between the seeds in a row initially differs, the value of the coefficient of variation of this distance is different from zero. This fact limits the use of the coefficient of variation as an indicator of the quality of the sowing machine with this method of seeding. Since with this method, the theoretical coefficient of variation is initially higher than 33 % [6].

Therefore, it is of particular importance to develop an intelligent system that will improve the way to assess the accuracy of dotted-nest sowing machines, and will also allow for pre-sowing adjustment of rowed seeders.

Theoretical research

The performance characteristics of a vacuum sowing machine depend on the diameter of the suction ports and the amount of vacuum pressure in the vacuum chamber. The suction coefficient depends on the size and shape of the seeds, the roughness of their surface, adhesion to other seeds and varies widely. In practice, the values of these parameters are set in such a way as to ensure guaranteed capture of the seed by the suction port. At the same time, as a rule, it is possible to avoid zero feeds, but a large number of group feeds appear (more than one seed is captured by one suction port), their presence also negatively affects the requirements for further growth and development of plants.

To eliminate group feeds in the design of vacuum sowing machines, a puller for excess seeds is provided. On the vast majority of modern devices of this type have flat, stepped (saw tooth) pressure pullers. Under their action, a group of seeds shifts to the axis of rotation of the sowing disc, and those of them that were fixed at the suction portfall back into the seed chamber in the worst case. The suction force of the seed to the opening of the disc depends on the vacuum pressure in the vacuum chamber and the area of the port.

Figure 1 shows a diagram of the dotted-nesting method of seeding on the sowing disc.

The total number of holes on the seeding disc is determined by their number in group k and the number of N_d groups. The angle between the holes in a group is designated as α, and the central angle between the centers of the extreme holes of neighboring groups is denoted by β.

The circumference of the sowing disc, on which the groups of holes are located, can be represented as:

$$N_d((k-1)\alpha+\beta)=2\pi. \quad (1)$$

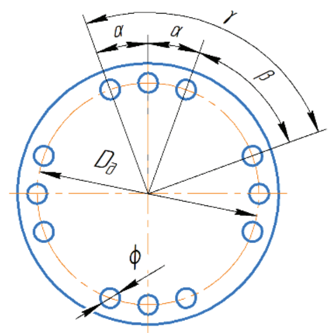


Fig. 1. The diagram of a dotted-nest sowing disk

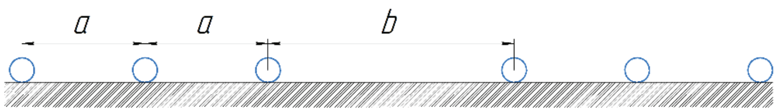


Fig. 2. The seed placement scheme in a row

Converting expression (1), with the design parameters of the seeding disk: $k = 3$, $\alpha/\beta = 1/2$, we obtain the following $\alpha = \pi/(2N_d)$, $\beta = \pi/(N_d)$.

The distance between the seeds in a row depends on the seeding rate, the speed of the sowing machine, and the rotation frequency of the sowing disc. Figure 2 shows this relation.

The time of separation of seeds from the disc of the sowing machine depends on the rotation frequency and the angle of placement of holes on the sowing disc, and was determined by the following formula:

$$T = \frac{\Omega}{\omega} = \frac{30\Omega}{\pi n}\frac{\pi}{180} = \frac{\Omega}{6n}, \tag{2}$$

where Ω is the angle between the holes of the sowing disk, °; n is the rotation frequency of the sowing disk, rpm; ω is the rotation frequency of the sowing disk, s^{-1}.

Table 1 shows the values of the time of passage between seeds through the seeding sensor, depending on the speed and angle of the holes.

Table 1

The theoretical values of seed flight time depending on the design and technological parameters of the sowing apparatus

Rotation speed of the sowing disc, rpm	Seed flight time, ms	
	α = 5°	β = 10°
15	56	112
20	42	84
25	33	66
30	28	56
35	28	56
40	21	42
45	18	36
50	16	33
55	15	30

The values of the mathematical expectation, standard error and coefficient of variation will depend on the placement scheme and the number of registered seeds.

The mathematical expectation of the dotted-nest sowing method M is determined by the following formula:

$$M = \frac{\sum t_g}{K} = \frac{\sum \frac{t_\alpha (k-1) + t_\beta}{k}}{K}, \tag{3}$$

where K is the number of seed groups, pcs; t_g is the time of flight of flight of the group of seeds, s; t_α is the time of flight between the seeds in the group, s; t_β is the time of flight between seed groups, s.

Given that the number of seeds m is the product of the number of seed groups K and the number of seeds in each group k, by converting formula (3) we obtain

$$M = \frac{k}{m} \sum \frac{t_\alpha (k-1) + t_\beta}{k}. \tag{4}$$

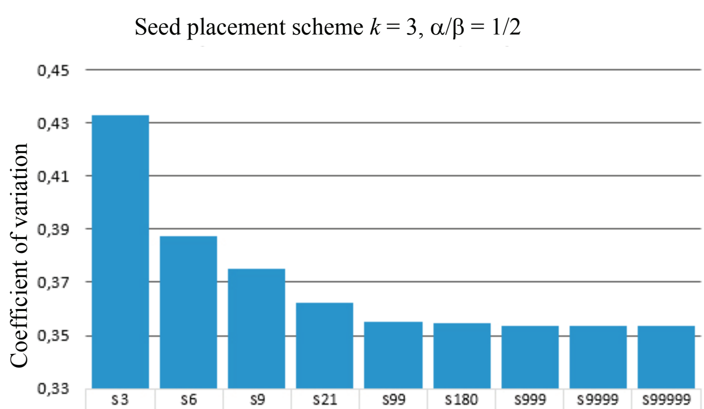
The standard deviation of the dotted-nest sowing method

$$\sigma = \sqrt{\frac{1}{m}\sum_{i=1}^{m}(x_i - M)^2} = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(x_i - \frac{k}{m}\sum \frac{t_\alpha (k-1) + t_\beta}{k}\right)^2}. \tag{5}$$

Coefficient of variation of the dotted-nest sowing method

$$\vartheta = \frac{\sigma}{M} = \frac{\sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(x_i - \frac{k}{m}\sum \frac{t_\alpha (k-1) + t_\beta}{k}\right)^2}}{\frac{k}{m}\sum \frac{t_\alpha (k-1) + t_\beta}{k}}. \tag{6}$$

Figure 3 shows a graph of the change in the theoretical coefficient of variation when modeling the dotted–nest sowing method.



	s3	s6	s9	s21	s99	s180	s999	s9999	s99999
ROW1	0,433013	0,387298	0,375	0,362284	0,355353	0,35454	0,35373	0,353571	0,353555

Fig. 3. Change in the theoretical coefficient of variation depending on the number of seeds

As can be seen from Figure 3, with the design parameters of the sowing disc, when the coefficient of variation of $\alpha/\beta = 1/2$ of the seed distribution of the dotted-nest sowing method tends towards 0.3535.

In order to assess the quality of seed sowing, in addition to well-known indicators (coefficient of variation, number of seeds per linear meter), accuracy of seed placement was also used.

When determining the accuracy of the dotted-nest sowing method, the number of seeds in each group, the distance between seeds in a group, and the distance to the next group were controlled. If the number of seeds did not correspond to the set number ($k = 3$) or the interval between seeds deviated from the set one standard error, then this group of seeds was rejected [7].

$$\begin{cases} | t_\alpha - t_i | < \sigma t_\alpha; \\ | t_\alpha - t_{i+1} | < \sigma t_\alpha; \\ | t_\beta - t_{i+2} | < \sigma t_\alpha. \end{cases} \quad (7)$$

The accuracy was calculated as a percentage of the formed seed nests to the total number of seeds.

$$P = \frac{kp}{N} 100\,\%, \quad (8)$$

where P is the seeding accuracy, %; p is the number of seed nests formed, pcs; N is the total number of seeds sown, pcs.

The solution of practical problems using mathematical methods was achieved by implementing the following algorithm:

– development of a mathematical model;

– the choice of a method for conducting research on the mathematical model;

– analysis of the obtained mathematical result.

A mathematical model is a system of formulas, functions, and equations that describes various phenomena, processes, and objects as a whole. When developing a model, it is necessary to take into account all the really existing relations of factors and parameters, although at the sametime we must not forget about the possibility of solving the mathematical model [8, 9] in the future.

Currently, three methods of constructing mathematical models are used: analytical, experimental, and experimental-analytical.

Since there is a large amount of data on the results of the sowing machine, this work uses an experimental method to build mathematical models. For this purpose, the theory of planning a multifactorial experiment is applied [10].

Materials and methods

In the course of laboratory experiments, the time of passage of seeds through the sensor's sensitive elements was measured on a millisecond accuracy scale. The total time of flight (T_0) of a seed through the sensor (Fig. 4) was determined by the time of flight of one seed (T_1) and the time between seeds (T_2). The data obtained were entered into log files and visualized in the form of a graph. The graphical data was saved on a computer and processed using mathematical statistics with software tools such as Mathcad, Microsoft Excel and Python [11].

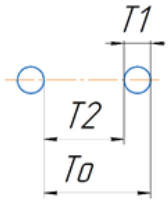


Fig. 4.The scheme for determining the time of seed flight through the seeding sensor

The design-mode parameters of the seeding apparatus were determined using the method of planning a multifactorial experiment. A planning matrix was used to determine the effect of three factors at three levels – 3^3, as shown in Table 2.

The rotation frequency of the sowing disc was adopted taking into account the speed of the sowing unit (5–7 km·h^{-1}) and the seeding rate (q = 400 thousand pcs·ha^{-1}), and varied in the range from 15 to 55 rpm. At a rotation speed of the sowing disc exceeding 45 rpm, termination of sowing was recorded due to an increase in centrifugal force and an insufficient vacuum discharge to hold the seeds in place in the holes of the sowing disc.

Table 2

The planning matrix for a multifactorial experiment

No.	The rotation frequency of the sowing disc	The position of the ejector	Seed fraction
1	–1	–1	–1
2	0	–1	–1
3	1	–1	–1
4	–1	0	–1
5	0	0	–1
6	1	0	–1
7	–1	1	–1
8	0	1	–1
9	1	1	–1
10	–1	–1	0
11	0	–1	0
12	1	–1	0
13	–1	0	0
14	0	0	0
15	1	0	0
16	–1	1	0
17	0	1	0
18	1	1	0
19	–1	–1	1
20	0	–1	1
21	1	–1	1
22	–1	0	1
23	0	0	1
24	1	0	1
25	–1	1	1
26	0	1	1
27	1	1	1

Table 3

Intervals and levels of variation of factors

Factors	Designation	Levels of variation		
		–1	0	+1
The rotation frequency of the sowing disc	X_1, rpm	15	35	55
The position of the seed ejector	X_2	–1/3	0	1/3
Seed fraction	X_3, mm	5.5	6	6.5

The position of the ejector depends on the diameter of the suction hole, the radius of the holes on the sowing disc, and other factors. The position of the seed ejector has been preliminarily determined, ensuring stable sowing.

So, when the hole was blocked by the ejector for more than 1/3 of its area, the seeds did not stick to the holes and sowing stopped. Therefore, the lower level (–1) of the variation factor (the position of the seed ejector) was assumed to be equal to 1/3. At zero (0) level, the ejector was located at the vertices of the holes according to their diameters. The upper level (+1) – the ejector is located at 1/3 of the top of the hole diameter, it is assumed that in this position, the seeds do not come into contact with the ejector.

Soybeans of the "Alaska" and "Lisbon" varieties of various fractions were used as seed material.

Taking into account the above, the levels and intervals of variation of these factors were determined, which are presented in Table 3.

Suppose that the model of the process under study is nonlinear, then the response function (Y) can be presented as a second-order polynomial:

$$Y = c_0 + c_1X_1 + c_2X_2 + c_3X_3 + c_4X_1X_2 + c_5X_1X_3 + c_6X_2X_3 + c_7X_1^2 + c_8X_2^2 + c_9X_3^2.$$

Based on the results of the analysis of the subject area, three indicators were selected as optimization criteria for the development of a mathematical model, with the help of which the seeding quality is assessed: the accuracy of the seed location (R_1), the crushing of seeds (R_2), the coefficient of variation of the time intervals (R_3) between the ejections of seeds from the sowing disc.

Results and their discussions

According to the method of processing the results of a multifactorial experiment, the average value and variance with 3-fold repetition for each experiment were determined, the dispersion of reproducibility and the value of the Cochran G-criterion were calculated, the values of the regression coefficients were computed (Table 4), the significance of the coefficients was determined taking into account the Student's *t*-criterion, the adequacy of the model was checked using the Fisher F-test.

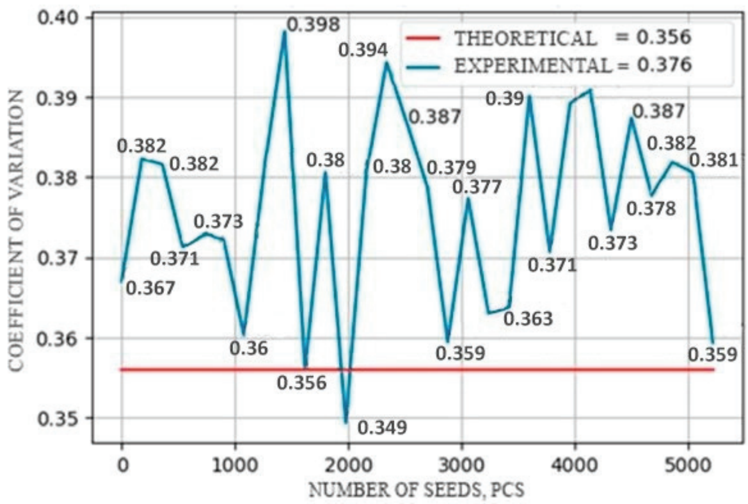
Checking the models using the Fisher criterion showed that, with a confidence interval of 95 %, the models for accuracy and seed fragmentation adequately describe the process under study ($R^2 > 0.96$), the model for determining the coefficient of variation turned out to be inadequate. The model does not describe the data well and does not determine the dependence between factors and response.

Figures 5, *a*, *b* show the change in the coefficient of variation during the operation of the sowing machine at the position of the seed dumper (0).

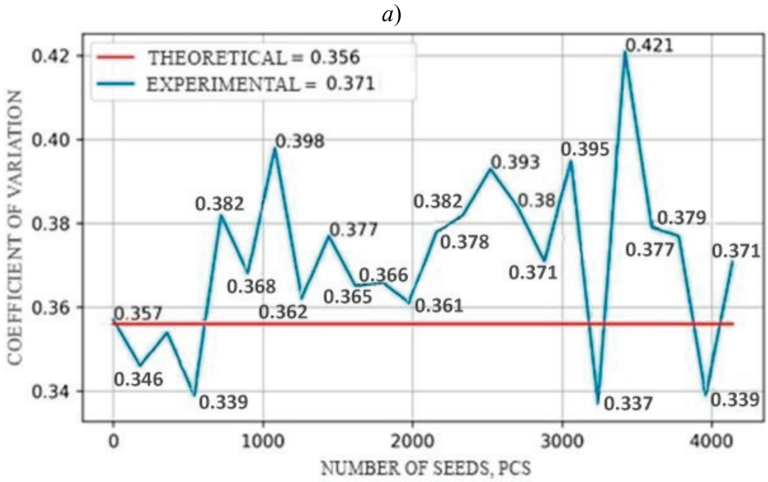
Table 4

Coefficients of the regression equation

Coefficients	Accuracy	Fragmentation	Variation
c_0	80.283	0.743	35.994
c_1	–12.499	1.333	–1.333
c_2	–5.688	0.598	0.589
c_3	0.352	–0.350	0.281
c_4	1.325	0.185	–0.644
c_5	–0.102	–0.363	0.348
c_6	0.987	–0.054	–0.858
c_7	–4.677	0.859	1.015
c_8	–7.041	0.016	1.567
c_9	3.790	0.054	–0.162



a)



b)

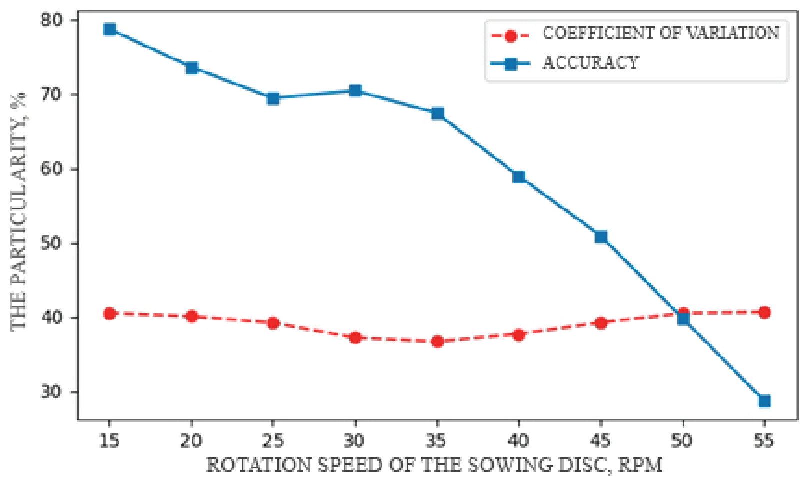
Fig. 5. Change in the coefficient of variation of the time intervals of the dotted-nest sowing method at a rotation speed of 15 (*a*) and 55 (*b*) rpm

As can be seen from the graphs, with an increase in the rotation frequency of the sowing disc, the centrifugal force also increases and when the seeds interact with the ejector, the vacuum in the vacuum chamber is insufficient, as a result of which the seeds are removed from the holes and fall back into the seed chamber of the sowing apparatus. As a result, gaps appear, nests are not formed and seeds are distributed more evenly, in consequence of which the coefficient of variation takes values less than the theoretical one.

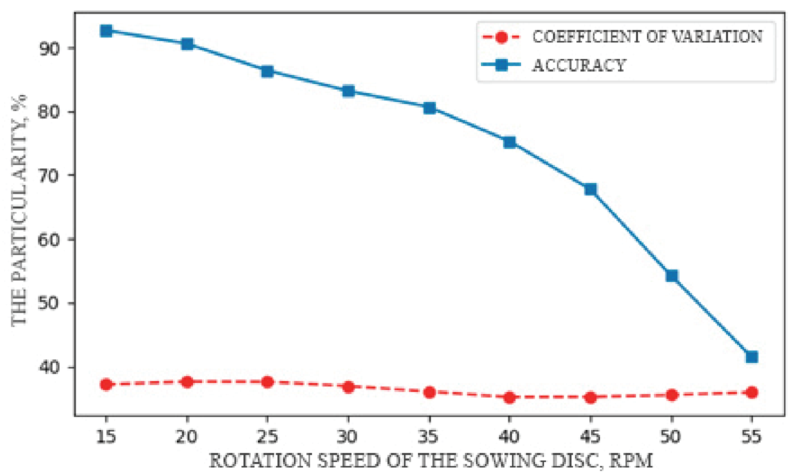
Figure 6 shows a comparison of accuracy and coefficient of variation.

As can be seen from the graphs in Fig. 6, an increase in the rotation frequency of the sowing disc leads to a worsening of the uneven distribution of seeds, gaps and duplicates appearing, which reduces the accuracy of the dot-nesting method. At the same time, the average value of the total coefficient of variation remains practically unchanged and ranges from 0.5 %.

The tendency to decrease the accuracy of dotted-nest sowing with slight fluctuations in the coefficient of variation with increasing rotation frequency of the sowing disc was observed on all studied soybean varieties.



a)



b)

Fig. 6. The average value of the coefficient of variation and accuracy:
a – the position of the seed ejector (–1/3); *b* – the position of the seed ejector (1/3)

Analyzing the graphs of Figs. 5, 6, it can be concluded that the use of the coefficient of variation as a criterion for evaluating the quality of the dotted-nest sowing method is impractical, since it does not adequately reflect the course of this sowing method.

When determining the significance of regression coefficients for seeding accuracy, it turned out that seed size (X_3) does not have a statistically significant effect and changing this factor does not lead to significant changes in response. Therefore, in order to simplify the model, this factor has been excluded from the regression equation.

When determining the significance of regression coefficients for seed fragmentation, it turned out that coefficients with a linear effect on controlled factors were significant. As can be seen from Table 4, the coefficient for the seed size factor (X_3) ($c_3 = -0.35$) had the least effect on the response, although the physical and mechanical properties of different soybean varieties differ, an assumption was made to simplify the model and this factor was excluded.

As a result, the following mathematical models were obtained for the development of the knowledge base, taking into account the significance of the regression coefficients:

$$R_1(X_1, X_2) = 80.28 - 12.5X_1 - 5.69X_2 + 1.325X_1X_2 - 4.68X_1^2 - 7.04X_2^2; \quad (9)$$

$$R_2(X_1, X_2) = 0.743 + 1.33X_1 + 0.6X_2 + 0.185X_1X_2 + 0.86X_1^2. \quad (10)$$

The following assumptions have been made to comply with agricultural requirements:

− rotation speed < 45 rpm;

− fragmentation< 1.5 %;

− seeding accuracy > 70 %.

The process of determining the optimization criteria was carried out using a simple parameter sweep method for X_1 and X_2, with step sizes of 5 for X_1 and 0.05 for X_2. The values of X_1 were varied from 10 to 60, and the values of X_2 were varied from 0.5 to 1. The resulting new values for the criteria R_1 and R_2 were recorded in a table.

For solving multi-criteria optimization problems, a Pareto front is constructed. This technique helps visualize which optimization criteria are most important and what trade-offs can be made in selecting the best solution. The goal of constructing the Pareto front in the context of the current system design is to identify a set of non-dominated solutions, providing a compromise between performance and seeding quality.

To construct the Pareto front, optimization criteria and parameters must be selected in such a way that they are interrelated. The chosen optimization criteria were two indicators used to evaluate seeding quality: the coefficient of variation of the time intervals (R_1) between seed discharges from the seeding disc, and seed fragmentation (R_2), both of which should be minimized.

Figure 7 presents the Pareto chart showing the variation of the coefficient of variation (R_1 min) and seed fragmentation (R_2 min) depending on the control factors X_1 (seeding disc rotation frequency, rpm) and X_2 (seed ejector position), taking into account the agro-technical requirements for precision seeding devices.

The optimal non-dominated solutions are located along the blue line on the graph. Considering the assumptions, all solutions are situated in the lower-left part of the graph, bounded by the red lines.

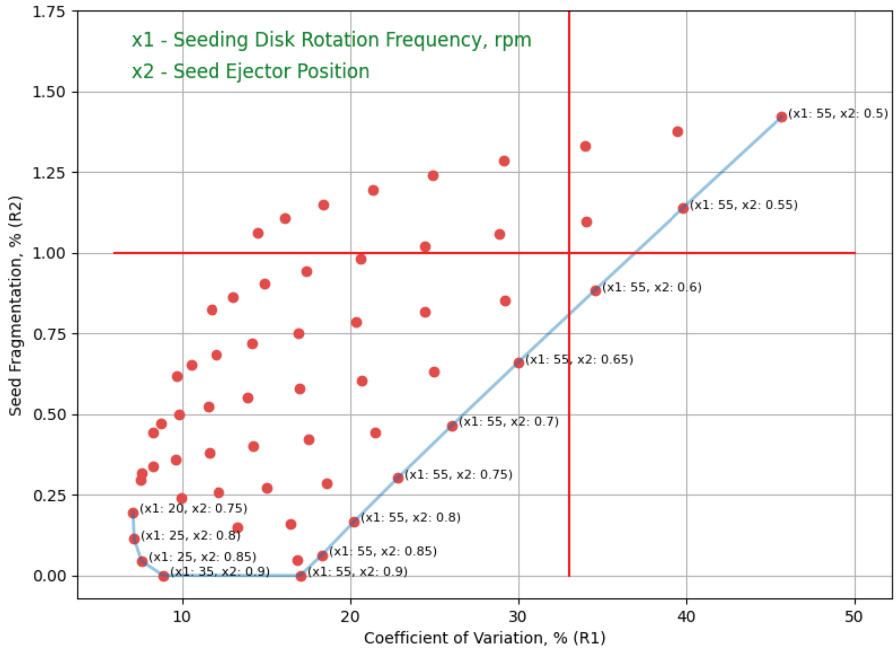


Fig. 7. Pareto Front

Conclusions

In this research work, a study was conducted on a method for evaluating the qualitative performance of a sowing machine using the dotted-nest sowing method, algorithms were developed to determine the accuracy of the method and to measure seed damage. The mathematical formulation of the problem is carried out and assumptions for the construction of a mathematical model are given, criteria for optimizing the determination of the quality of sowing are defined.

Using this approach will reduce the effort of specialists setting up seeders on a test bench before the sowing season, rather than in the field. Further work will be related to the development of software for an intelligent decision support system for determining the quality of sowing and its hardware.

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Математическое моделирование и оптимальное управление процессом высева семян пунктирно-гнездовым высевающим аппаратом

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Ключевые слова: высев; время высева; датчик высева; контроль высева; сбрасыватель семян; семена.

Аннотация: Представлен метод оценки качественных показателей работы высевающего аппарата при пунктирно-гнездовом способе посева. Осуществлен анализ предметной области, в рамках которого описан объект оптимизации.

Поставлена задача оптимального определения качества посева, для которой разработана математическая модель. Определен критерий оценки точности высева семян сои пунктирно-гнездовым способом. Для этого использованы методы планирования многофакторного эксперимента, статистического анализа, оптимизации, теории принятия решений.

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Mathematische Modellierung und optimale Steuerung des Saatprozesses mit einem punktierten Nist-Aussaatapparat

Zusammenfassung: Es ist eine Methode zur Leistungsbewertung eines Aussaatapparats mittels Punktnestverfahren vorgestellt. Eine Bereichsanalyse ist durchgeführt, in deren Rahmen das Optimierungsobjekt beschrieben ist. Das Problem der optimalen Bestimmung der Saatgutqualität ist formuliert und ein mathematisches Modell entwickelt. Ein Kriterium zur Bewertung der Genauigkeit der Sojabohnenaussaat mittels Punktnestverfahren ist definiert. Methoden der multifaktoriellen Versuchsplanung, der statistischen Analyse, der Optimierung und der Entscheidungstheorie sind angewendet.

Simulation mathématique et commande optimal du processus de semis avec un semoir à nid en pointillé

Résumé: Est présentée une méthode d'évaluation des performances qualitatives de l'appareil de semis dans la méthode de semis en pointillés. Est réalisée une analyse du domaine dans lequel l'objet d'optimisation est décrit. L'objectif est de déterminer de manière optimale la qualité du semis, pour laquelle un modèle mathématique a été mis au point. Est défini un critère d'évaluation de la précision de l'ensemencement des graines de soja. Sont utilisées des méthodes de planification d'expériences multifactorielles, d'analyse statistique, d'optimisation, de théorie de la prise de décision.

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